

Continuous - variable entanglement meets qubits

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Since its proposal more than 20 years ago [2], an experiment combining these two elements has remain elusive. It is predicted that one can distribute qubit entanglement using a spatially separated two-mode squeezed state. We show the stabilization of a weakly entangled state in the framework of circuit QED.

MOTIVATION

Continuous variable (CV) states are widely used for quantum computation but requiere the use of an ancillary non-linear system.

Similarly, they are useful for communication and sensing, yet the interface of CV entangled states with distant qubits was missing. It will allow to:

- * Build loss resilient quantum links.
- * First time observed the distribution of discrete variable entanglement from continuous variable entanglement.
- * Deterministic generation of weakly entangled states complementary to other existing protocols, e.g. deterministic state transfer only works for photon loss < 0.5.
- * Interface of a Gaussian state (TMSV) with qubits opens up the posibility of doing non-Gaussian operations, such as photon substraction which increases the squeezing.

TWO - MODE SQUEEZED VACUUM (TMSV)

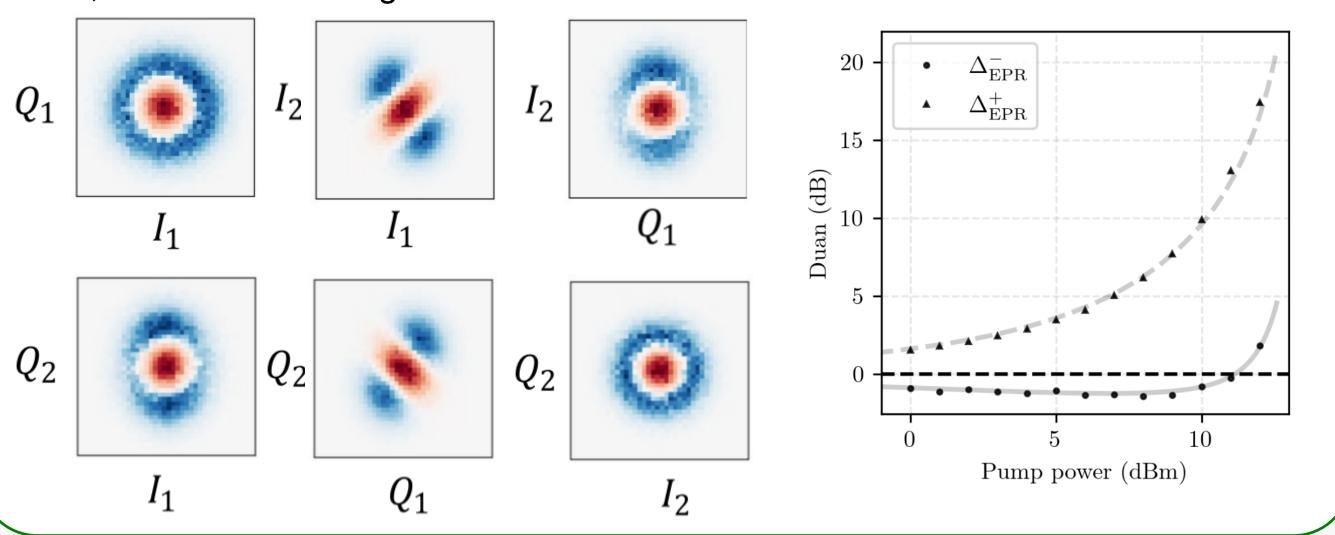
* A strongly pumped Josepshon Parametric Converter (JPC) supports a three-wave mixing process described by the Hamiltonian

$$H/\hbar = \omega_a a^{\dagger} a + \omega_b b^{\dagger} b + \chi(p+p^*)(a+a^{\dagger})(b+b^{\dagger}),$$

which under the right approximations is equal to the TMS Hamiltonian

$$H_{\chi} = i\chi(a_1^{\dagger}a_2^{\dagger}a_0 - a_1a_2a_0^{\dagger}) \simeq i\chi\alpha_0(a_1^{\dagger}a_2^{\dagger} - a_1a_2).$$

* The Duan criterion certifies that if the amount of squeezing goes below the vacuum level, it exists CV entanglement.

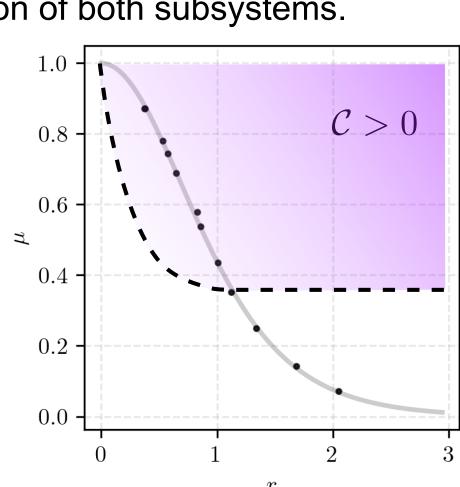


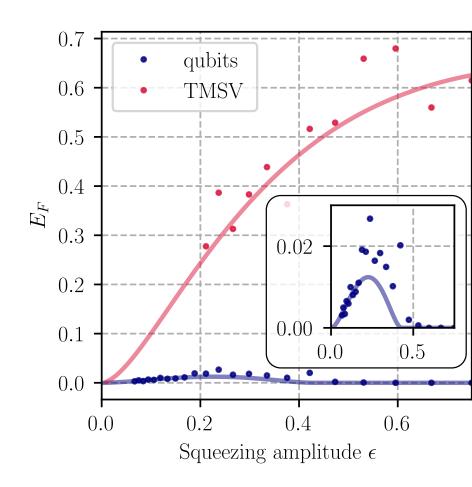
ENTANGLEMENT TRANSFER

* We can simulate the qubit state using the reduced master equation [1]

$$\dot{\rho}_q = \mathscr{L}_q \rho_q + \sum_{i=1,2} \sum_{s=\pm} \gamma_i N_i \mathscr{D}[\sigma_i^s, \sigma_i^{-s}] \rho_q - \sqrt{\gamma_1 \gamma_2} \{ M(\mathscr{D}[\sigma_1^+, \sigma_2^+] \rho_q + \mathscr{D}[\sigma_2^+, \sigma_1^+] \rho_q) + H.c. \}.$$

- * The purity of the TMS state must remain high to get entanglement in the qubits.
- * Qubit dephasing will destroy the entanglement and must remain lower than the qubit waveguide coupling.
- * Losses in the waveguide will affect the protocol, but entanglement survives beyond 50% loss.
- * We quantify the entanglement transfer efficiency by computing the Entanglement of Formation of both subsystems.



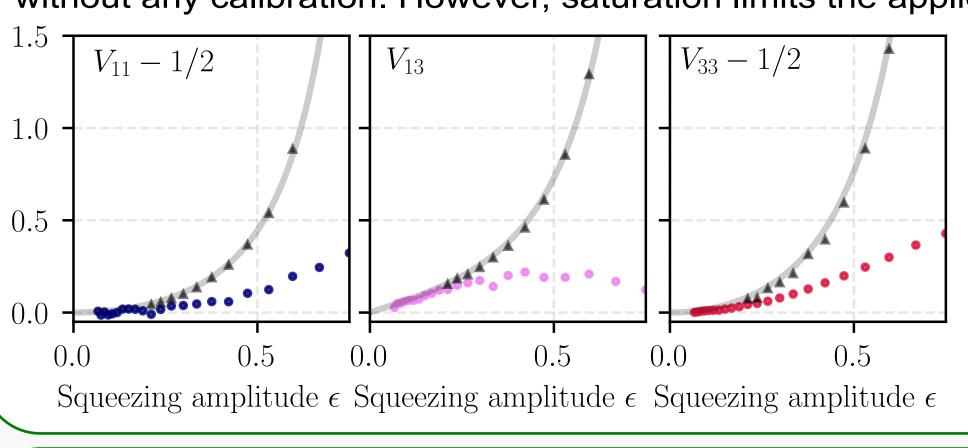


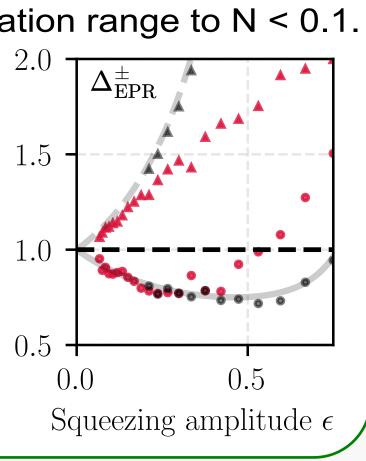
QUBITS ARE CORRELATION DETECTORS

We use the qubits as photodetectors and retrieve the photonic correlations from the linearized mapping

$$\{a,b\} \longrightarrow \{\sigma_-^{(1)},\sigma_-^{(2)}\}$$

In this way, we characterize the TMSV state at very low photon numbers and without any calibration. However, saturation limits the application range to N < 0.1.



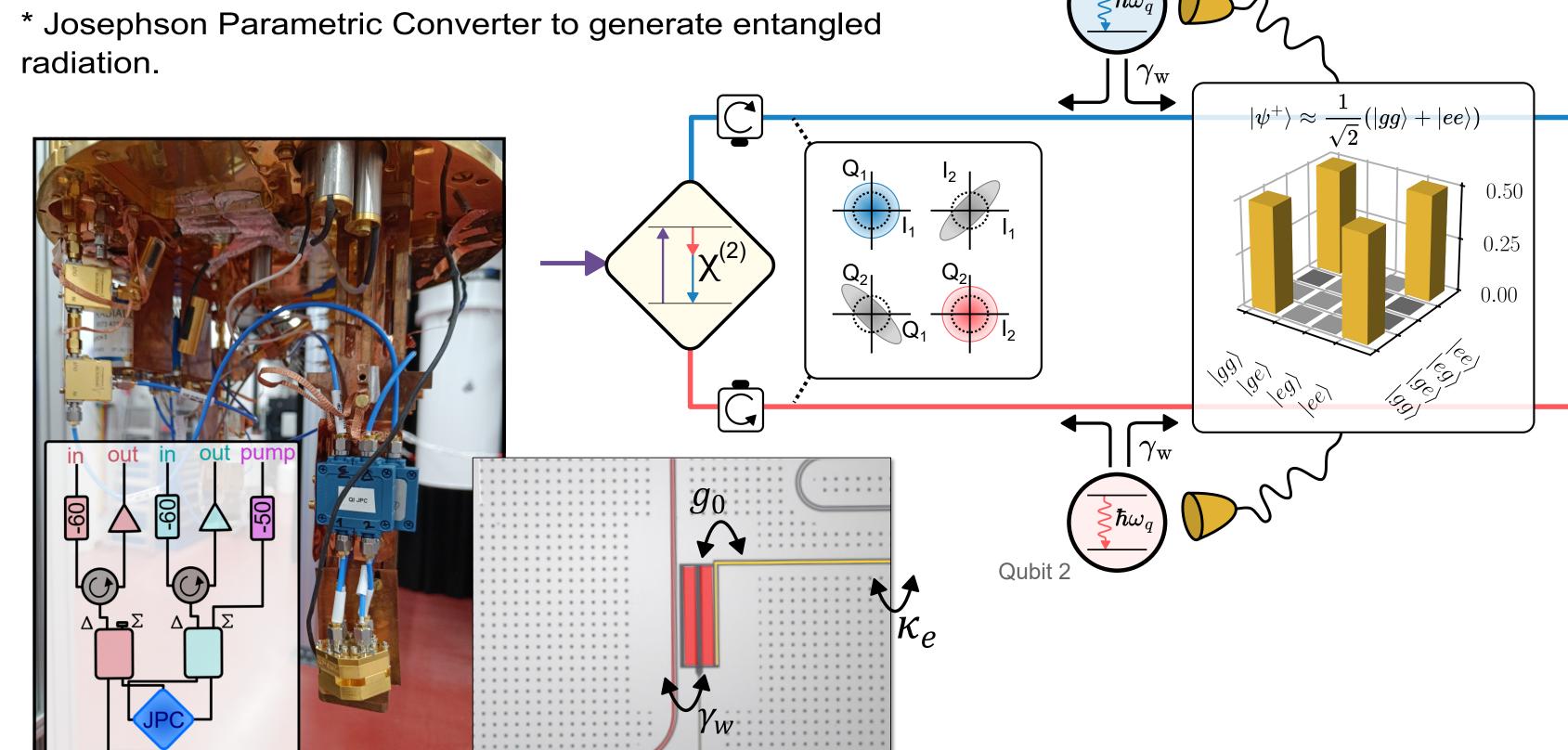


CONCLUSIONS

- * We show deterministic entanglement between two transmon qubits distributed over a distance of ~1 meter.
- * Entanglement can be improved by mitigating dephasing and increasing the bandwidth and purity of the squeezing to state-of-the-art values with Concurrence ~ 0.6
- * Steady-state storage of the entangled state is possible by adding one more qubit in each node, and extended to more than two qubits [3].

EXPERIMENTAL IMPLEMENTATION

* Two transmon qubits coupled to an open waveguide and a readout resonator.

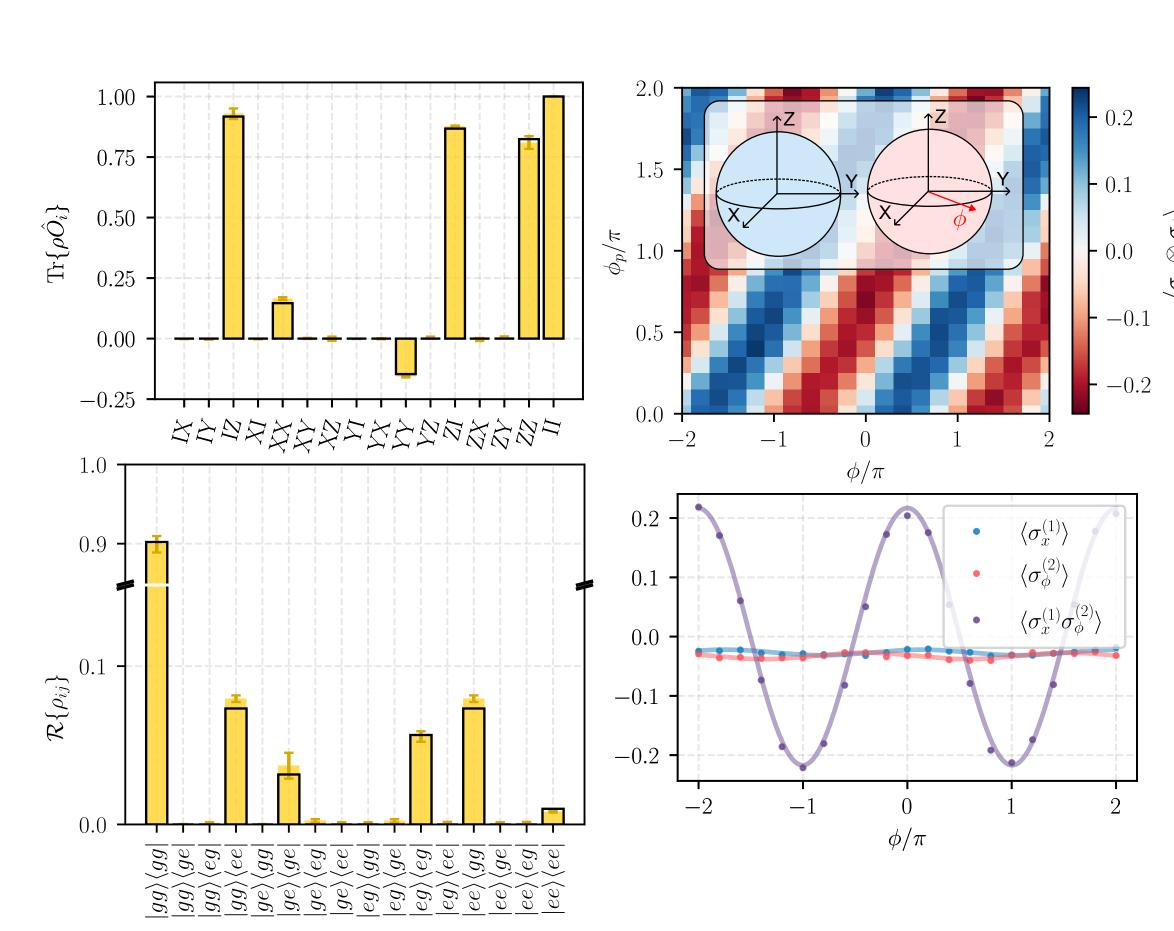


TOMOGRAPHY AND PHASE CONTROL

We send a pulse to the squeezer that translates into two pulses at the TMSV frequencies which drive the qubits. Immediately after we perform tomography by applying 25 different basis combinations {IX, IY, ... XX, XY, YX, .. ZZ}.

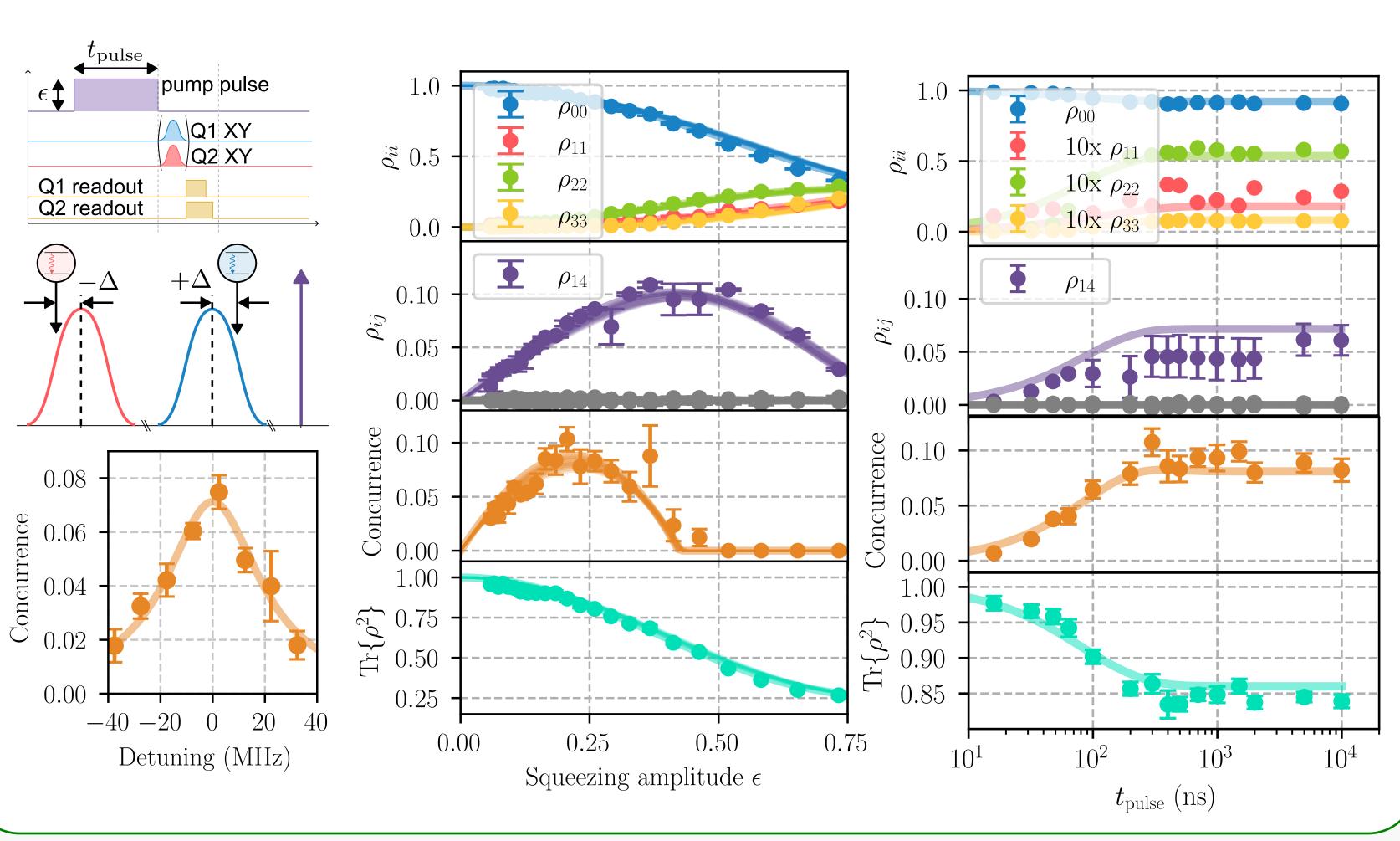
We reconstruct the density matrix usign a MLE.

Measuring only along the equator of the Bloch sphere, we see non-local phase coherence in an "interferometric measurement ".



ENTANGLEMENT CHARACTERIZATION

- * We reconstruct the density matrix of the qubit state for pulses of different length and squeezing strength. We observe that the maximum entanglement is reached at a finite squeezing amplitude due to asymmetries, losses and qubit dephasing.
- * We are able to stabilize the entangled state for up to 10 microseconds, while only the low SNR tomography and stability prevents us from going for longer times.
- * We detune the qubits from the center of the fields and observe how the correlations decay following an expected Lorentzian shape.



REFERENCES

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[2] Kraus, B., & Cirac, J. I. (2004). Discrete entanglement distribution with squeezed light. Physical review letters, 92(1), 013602.

[3] Agustí, J., Zhang, X. H. H., Minoguchi, Y., & Rabl, P. (2023). Autonomous distribution of programmable multiqubit entanglement in a Dual-Rail quantum network. Physical Review Letters,